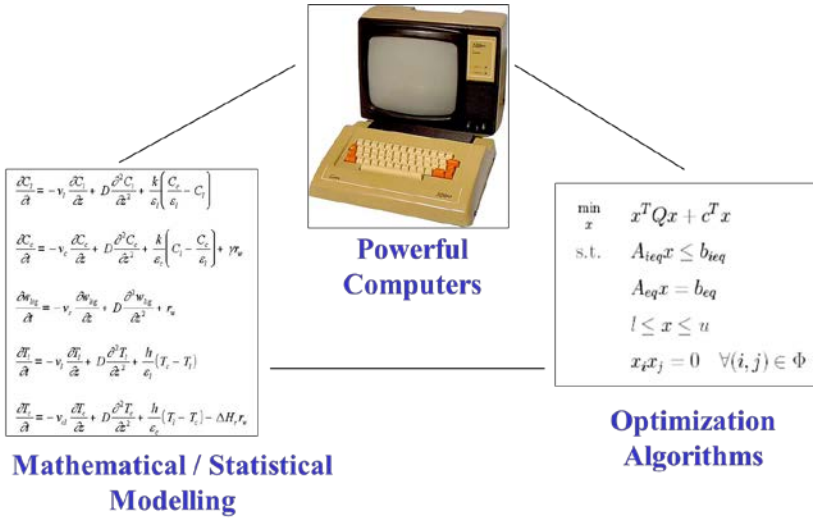
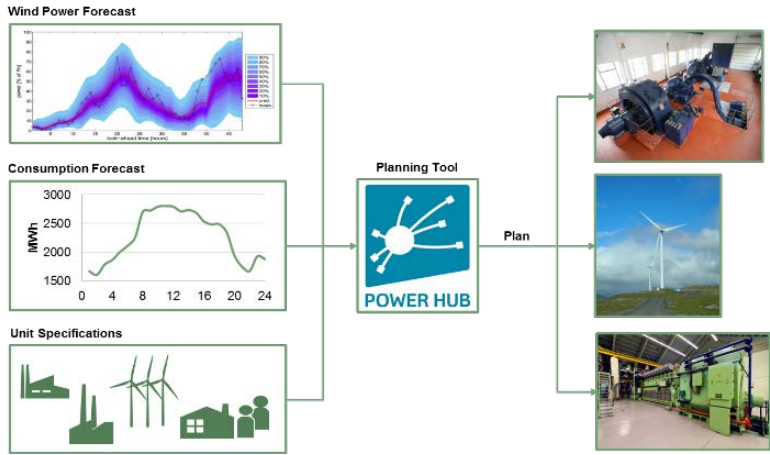


Model Predictive Control for Smart Energy Homes

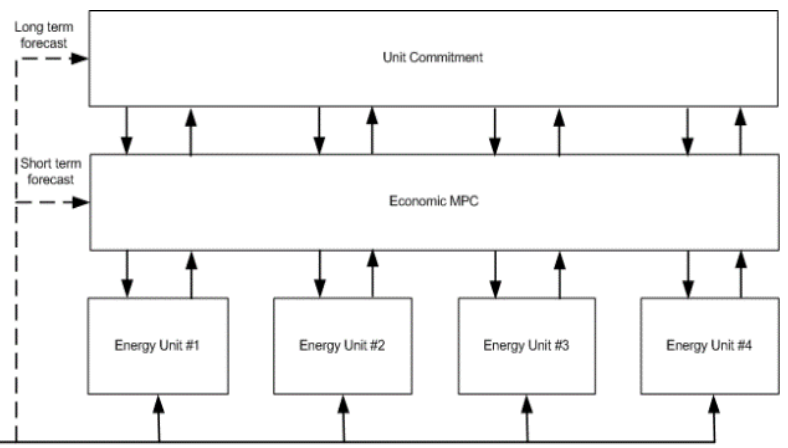
John Bagterp Jørgensen
Technical University of Denmark

100% Climate Neutrality
30 September – 2 October 2019
Sonderborg, Denmark

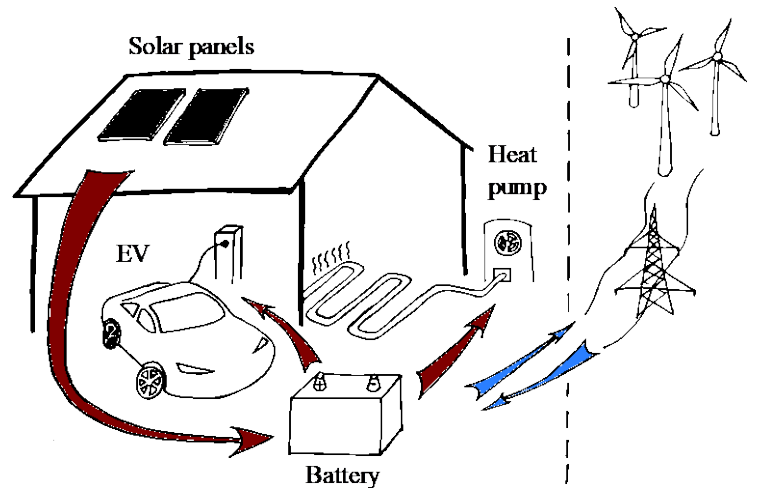
Optimization based control = Model Predictive Control (MPC)



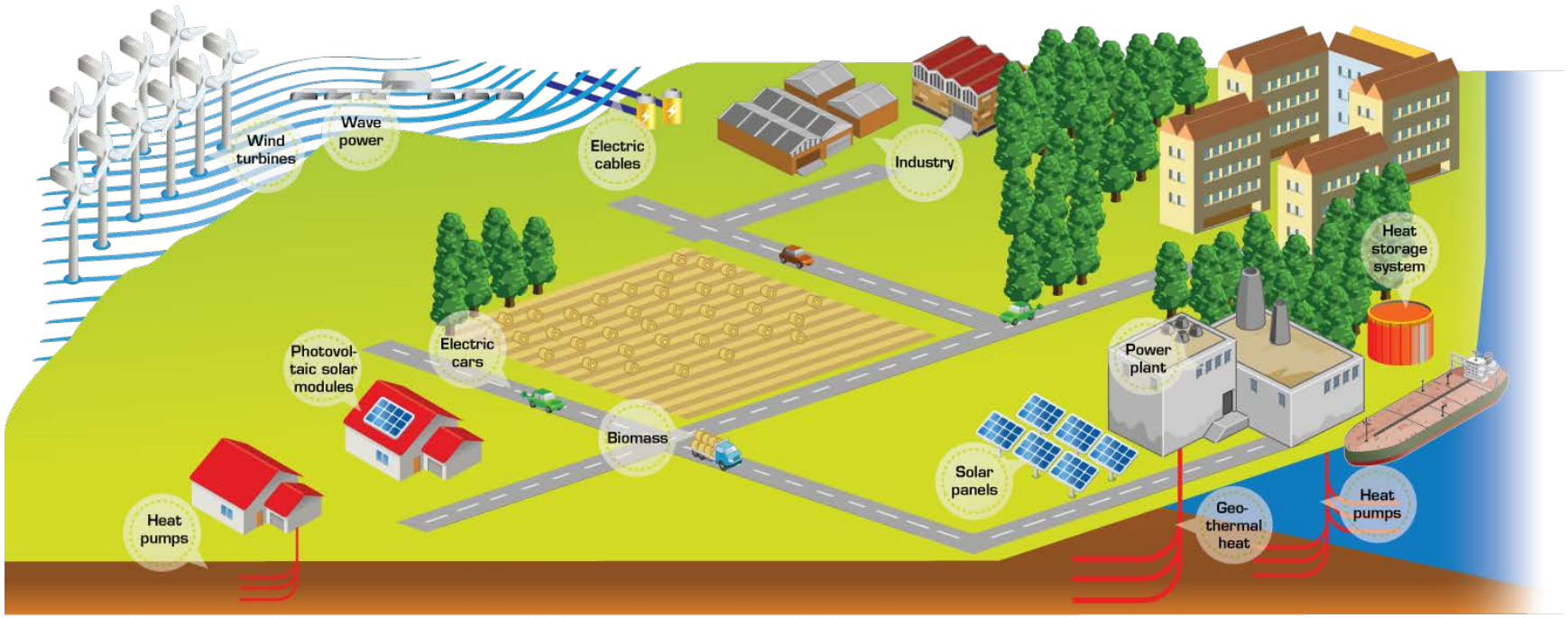
Hierarchical Control Structure



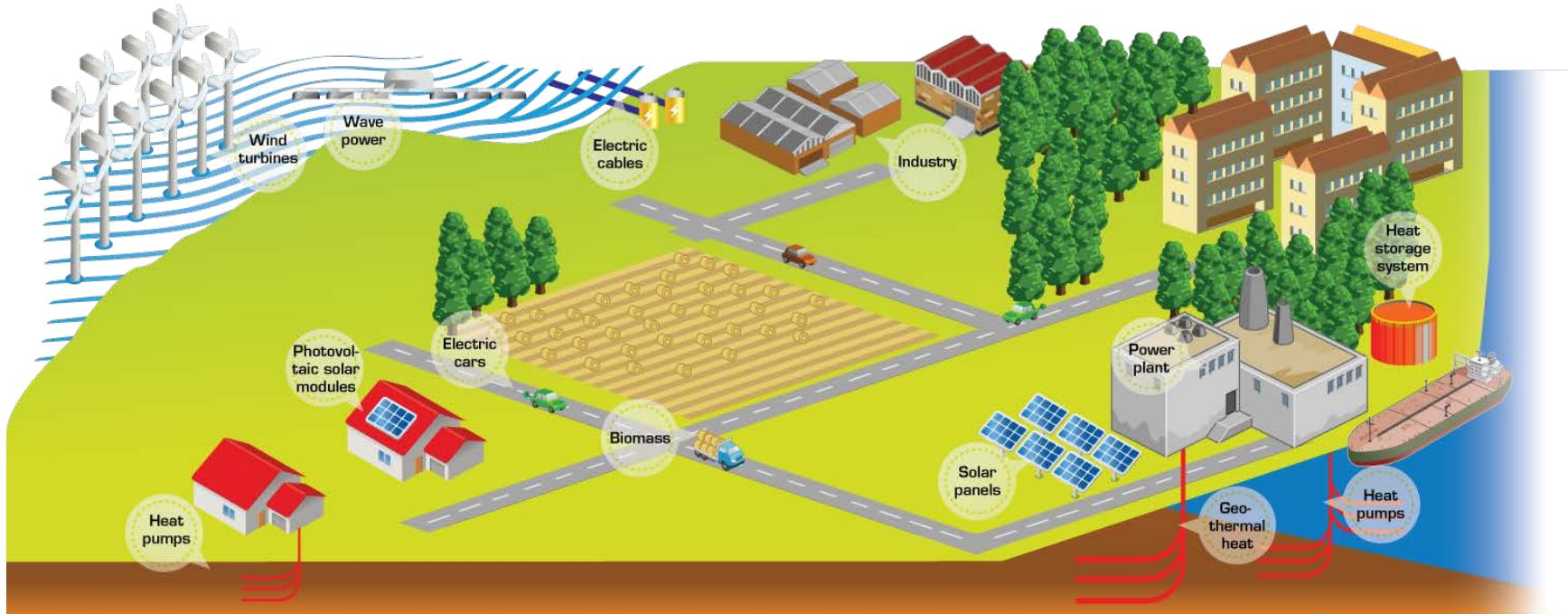
Disturbances
- wind speed
- ambient temp
- solar radiation



The Vision of Energy-Smart Cities



Smart Energy Systems



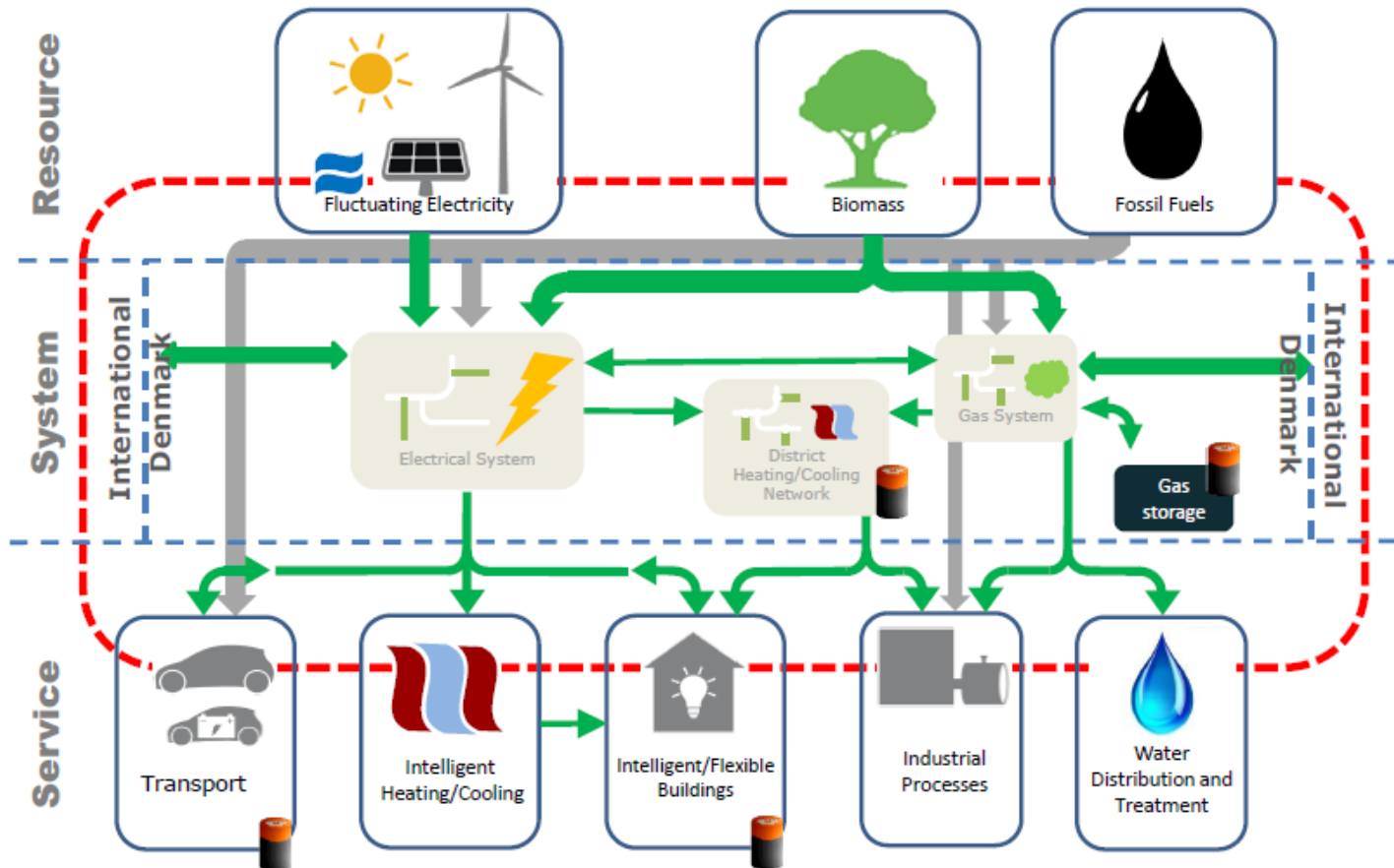
- **Thermal Storage**

- Heating of floors etc
- Heating of water accumulation tanks
- Refrigeration Systems

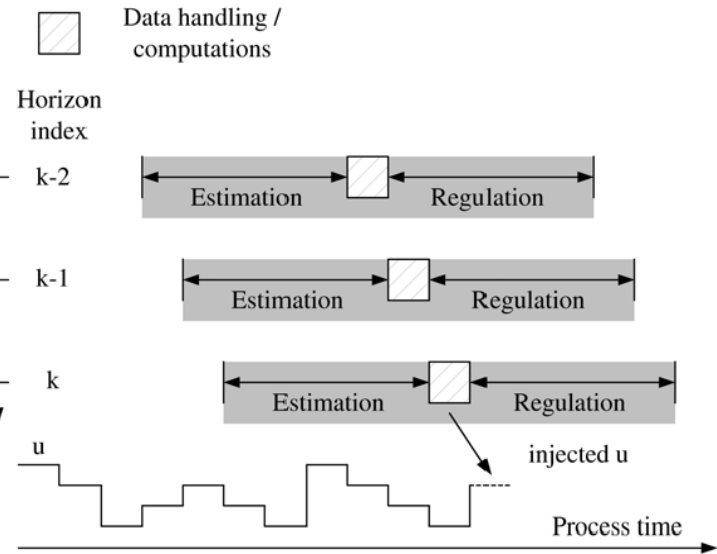
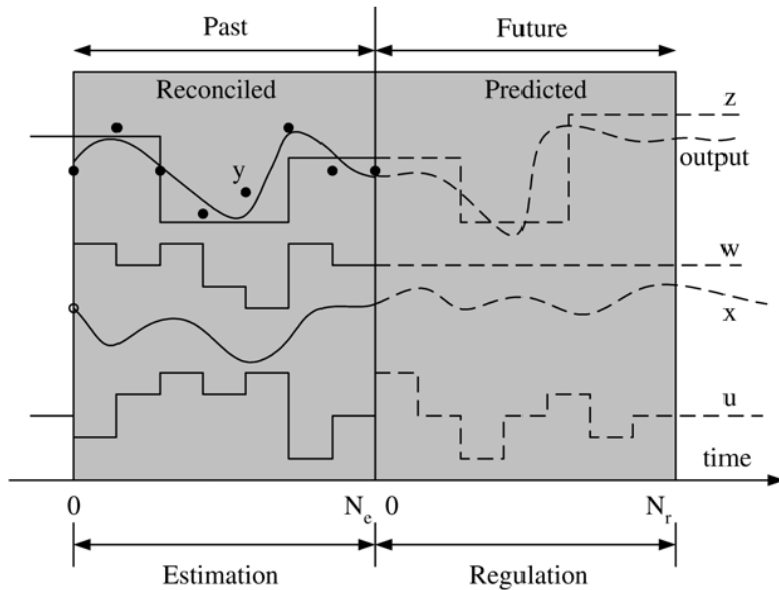
- **Power / Heat Producers**

- Wind Turbines
- Photovoltaic Solar Modules
- Solar Panels
- CHP Plants
- Fuel Cells

Connected and Integrated Energy Systems - Model Predictive Control is the enabler



Model Predictive Control

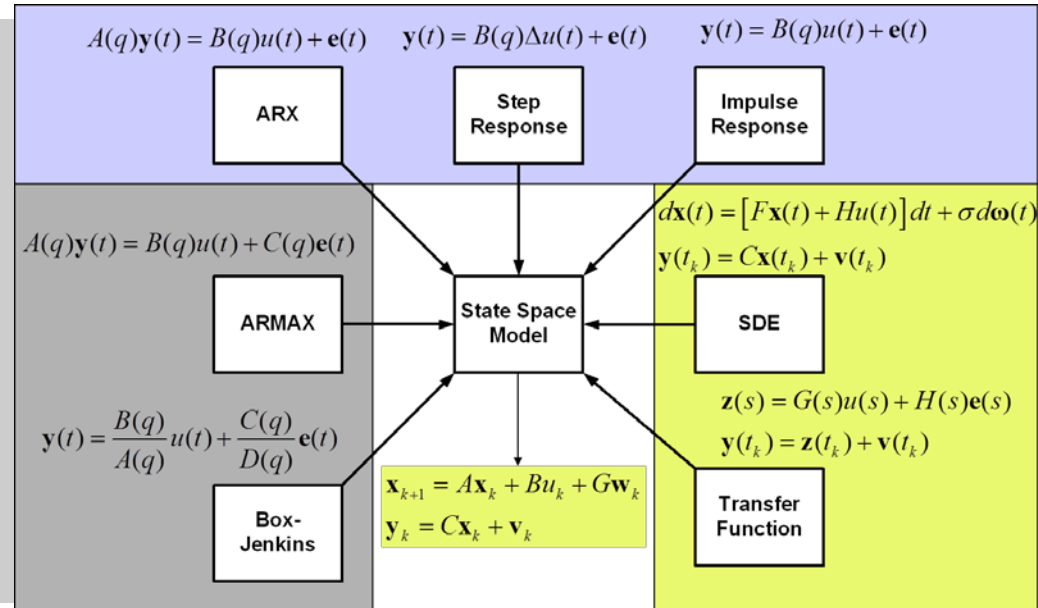
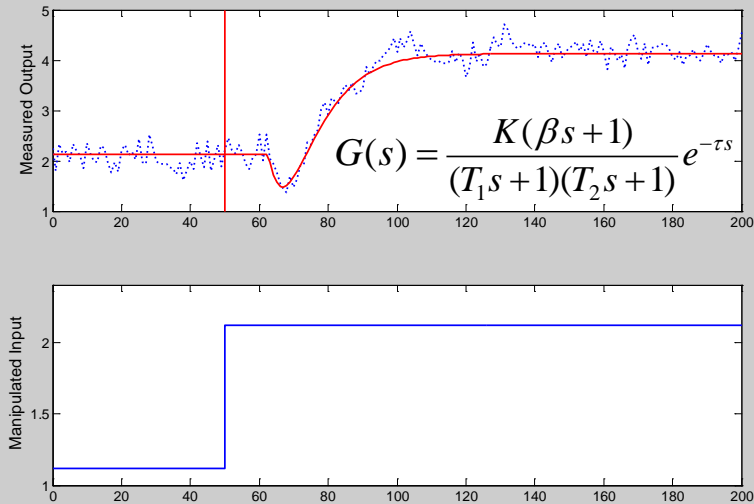


$$\min_{\{u_k, x_{k+1}\}_{k=0}^{N-1}} \phi = \phi(\{u_k, x_{k+1}\}_{k=0}^{N-1}; x_0, \theta)$$

$$s.t. \quad x_{k+1} = F_k(x_k, u_k, \theta) \quad k = 0, 1, \dots, N - 1$$

$$u_k \in \mathcal{U}$$

Data based prediction models

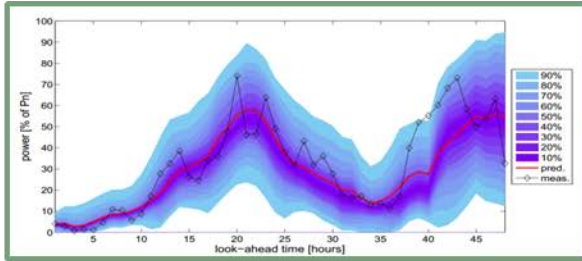


The models for filtering and prediction are

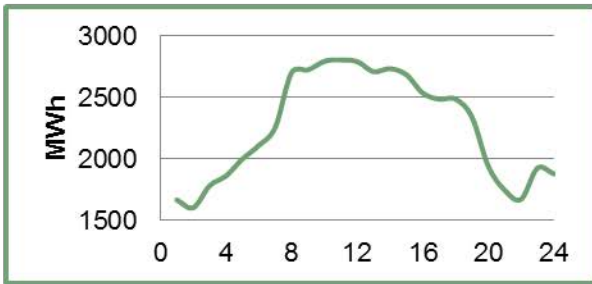
- Adaptive
- Data-based
- Combines a-priori (model) and a-posteriori (data) information
- Able to predict the mean values and the uncertainties

Control of Energy-Smart Systems = Economic Model Predictive Control

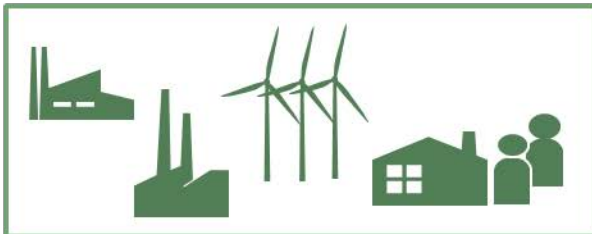
Wind Power Forecast



Consumption Forecast



Unit Specifications



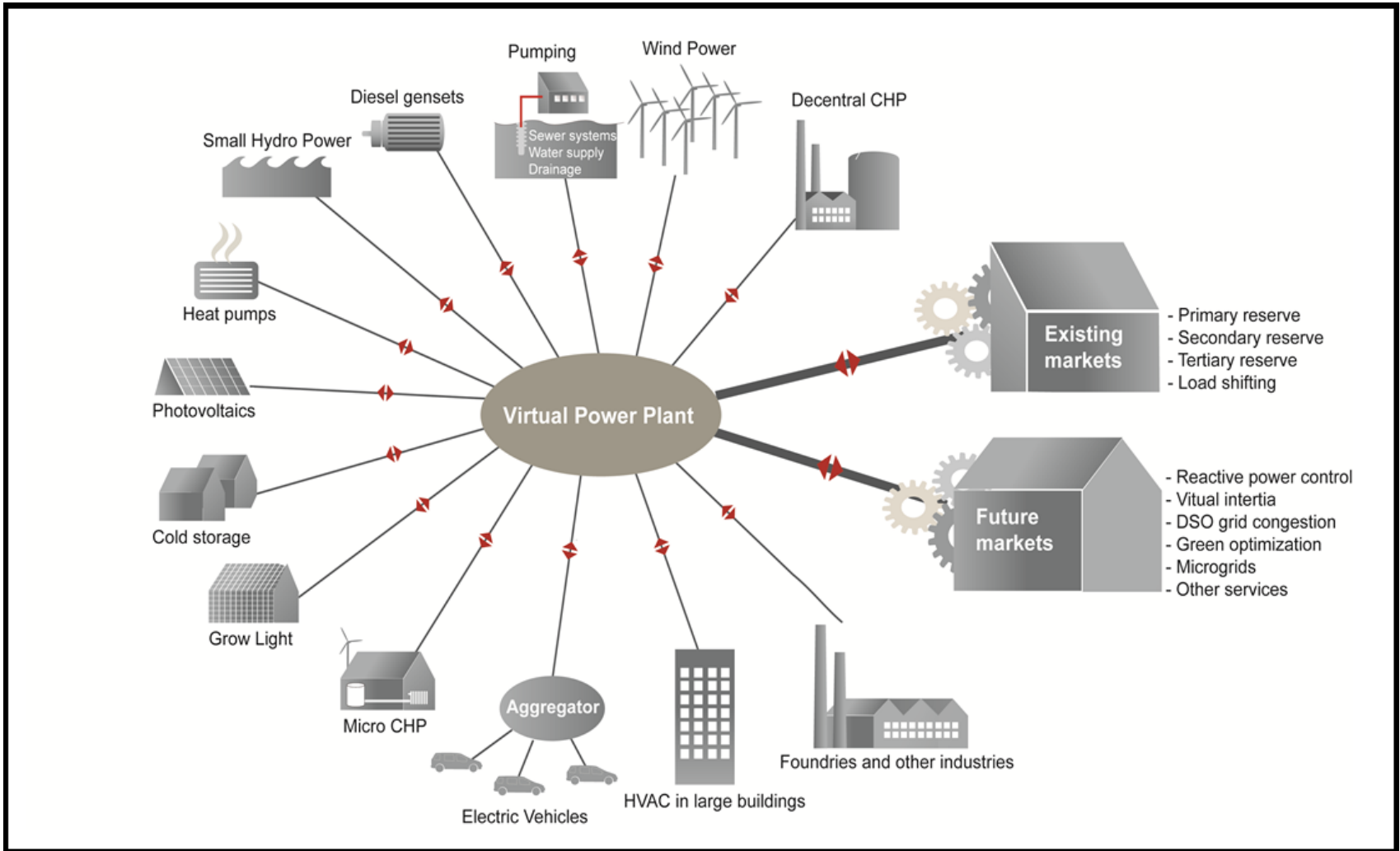
Planning Tool



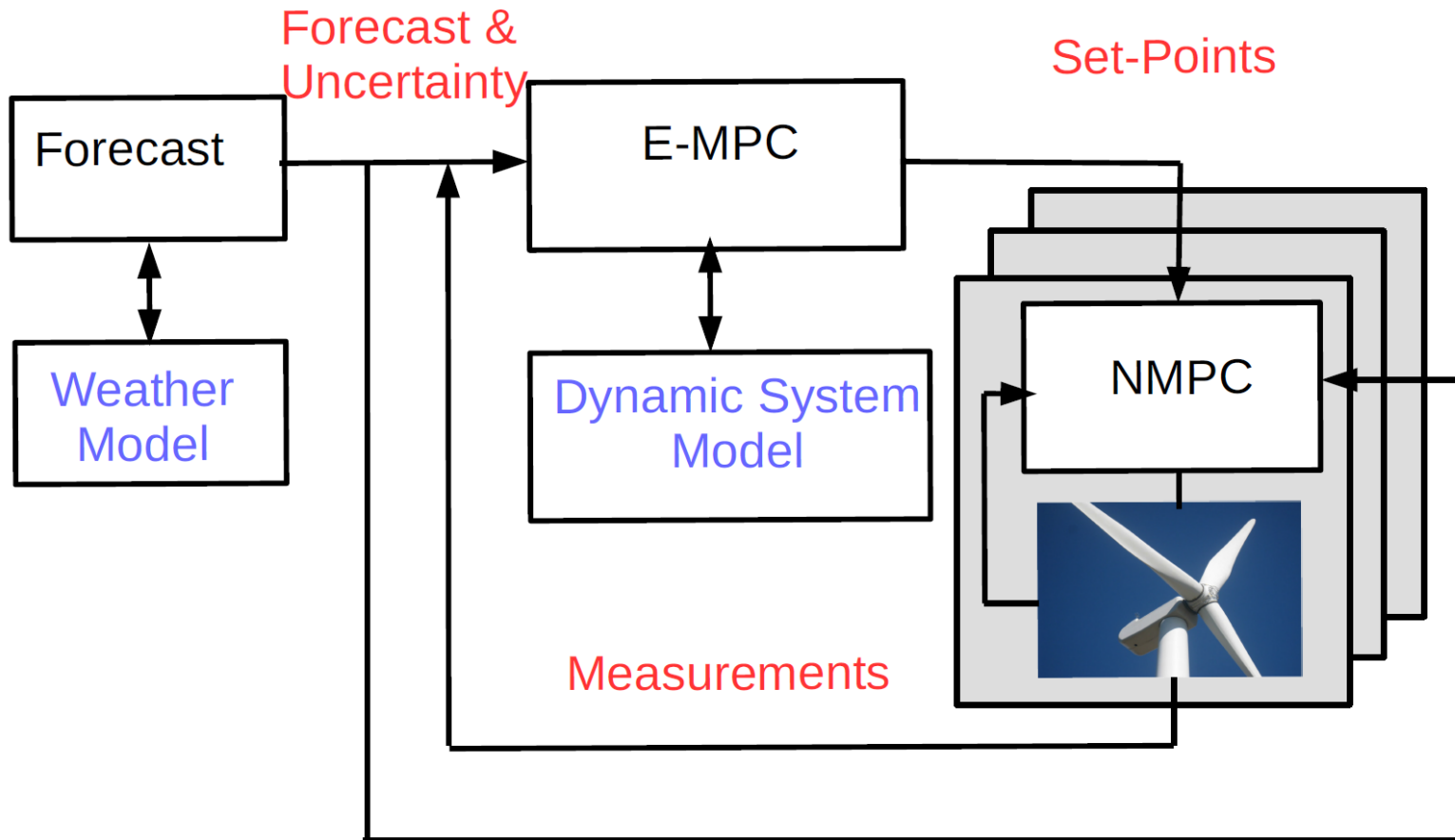
Plan



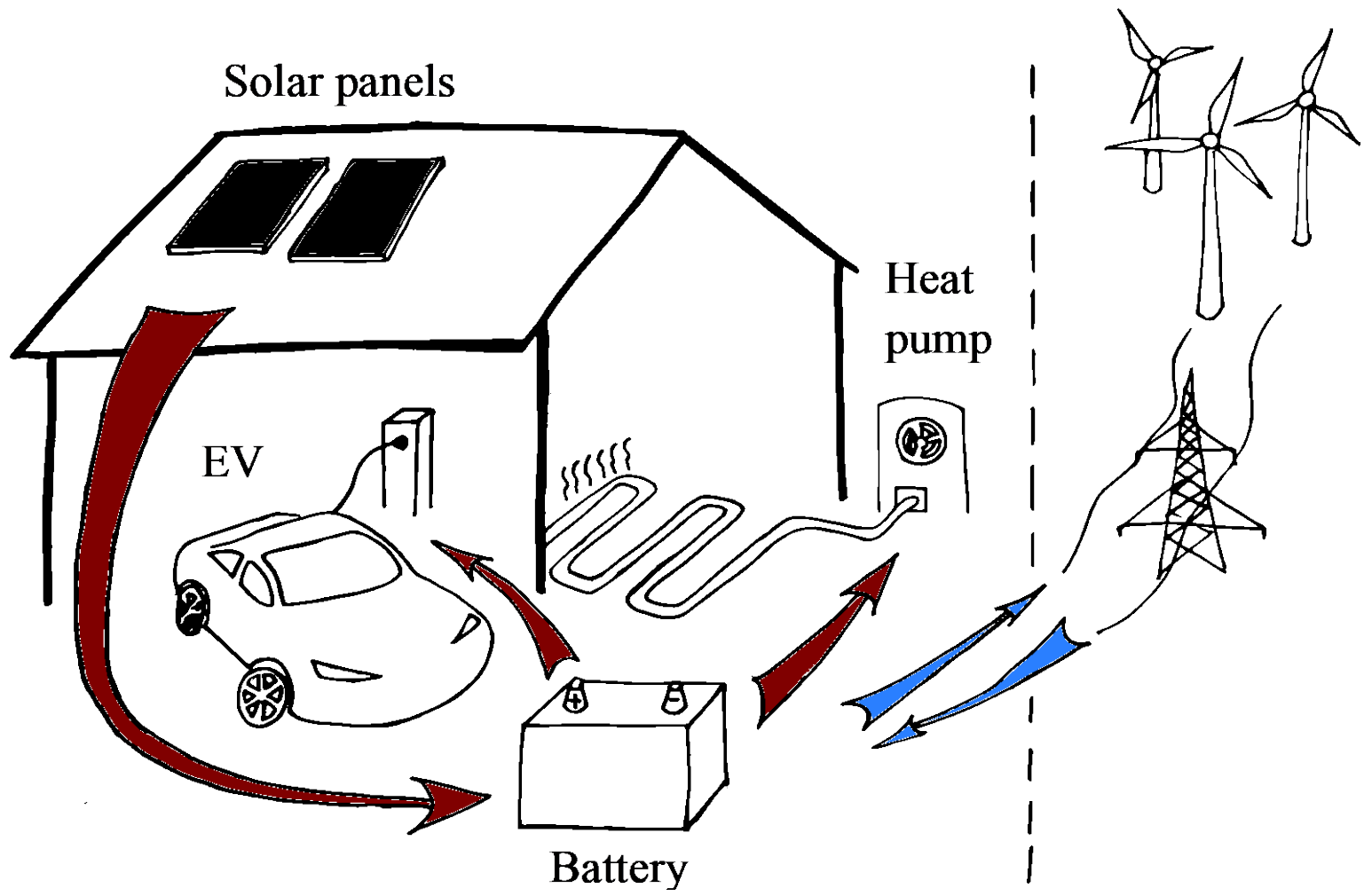
Virtual Power Plant



Forecast Based Hierarchical MPC



The Vision of Energy-Smart Homes



Elon Musk's vision of an energy-smart home



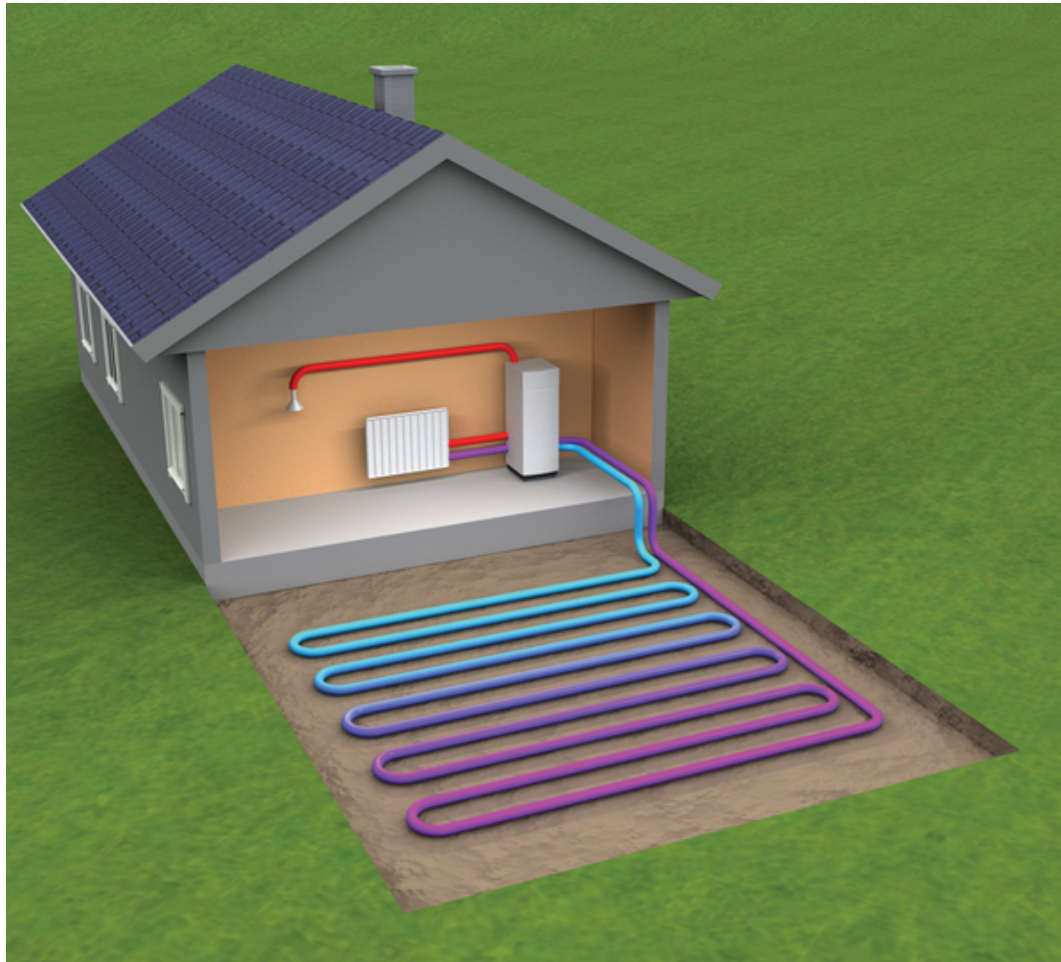
Electric Vehicles



Solar roof tiles



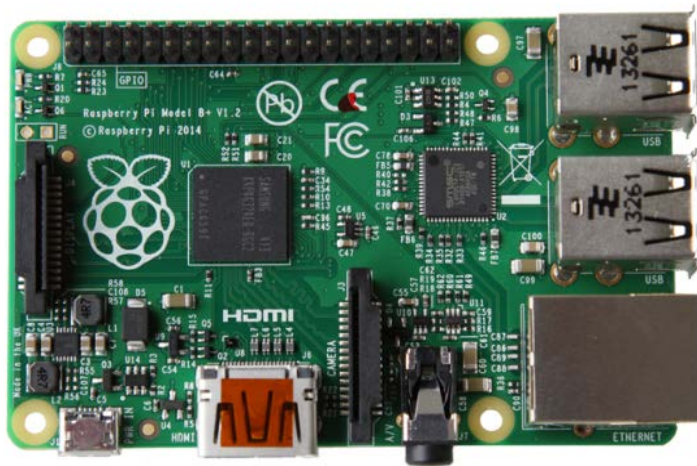
Heat Pumps



Smart Energy Consumption in a Residential Home

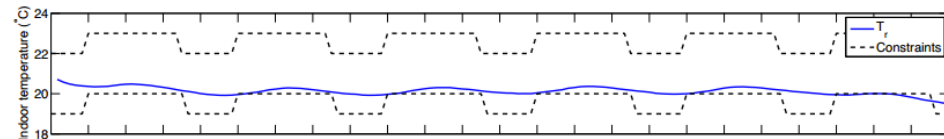
Raspberry Pi Embedded Control

Embedded MPC Algorithms for control of individual energy units



Control from the cloud

The control and forecasting systems are in the cloud.



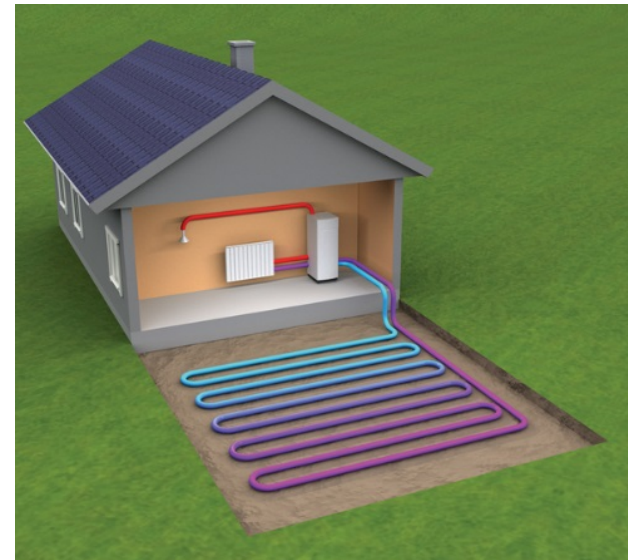
$$\min_{\{u_k, x_{k+1}\}_{k=0}^{N-1}} \phi = \sum_{k=0}^{N-1} l_k(x_k, u_k) + l_N(x_N) \quad (1a)$$

$$s.t. \quad x_{k+1} = A_k x_k + B_k u_k + b_k \quad k \in \mathcal{N} \quad (1b)$$

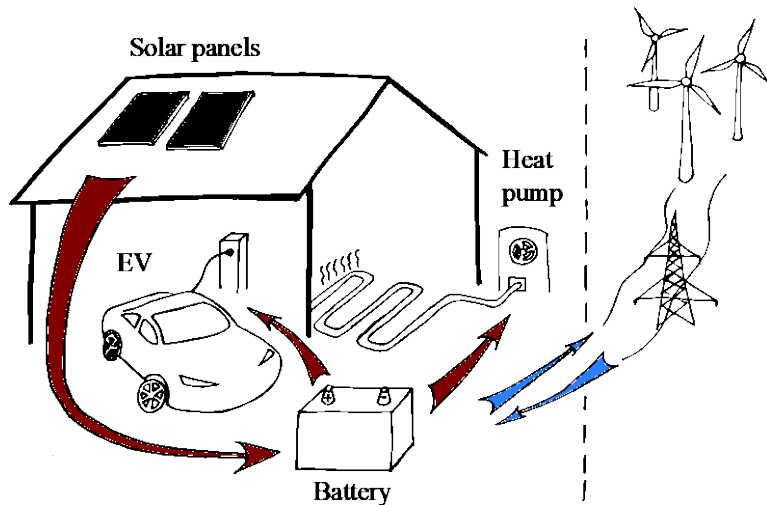
with $\mathcal{N} = \{0, 1, \dots, N-1\}$ and stage costs defined by

$$l_k(x_k, u_k) = \frac{1}{2} \begin{bmatrix} x_k \\ u_k \end{bmatrix}' \begin{bmatrix} Q_k & M_k' \\ M_k & R_k \end{bmatrix} \begin{bmatrix} x_k \\ u_k \end{bmatrix} + \begin{bmatrix} q_k \\ s_k \end{bmatrix}' \begin{bmatrix} x_k \\ u_k \end{bmatrix} + \rho_k \quad (2a)$$

$$l_N(x_N) = \frac{1}{2} x_N' P_N x_N + p_N' x_N + \gamma_N \quad (2b)$$



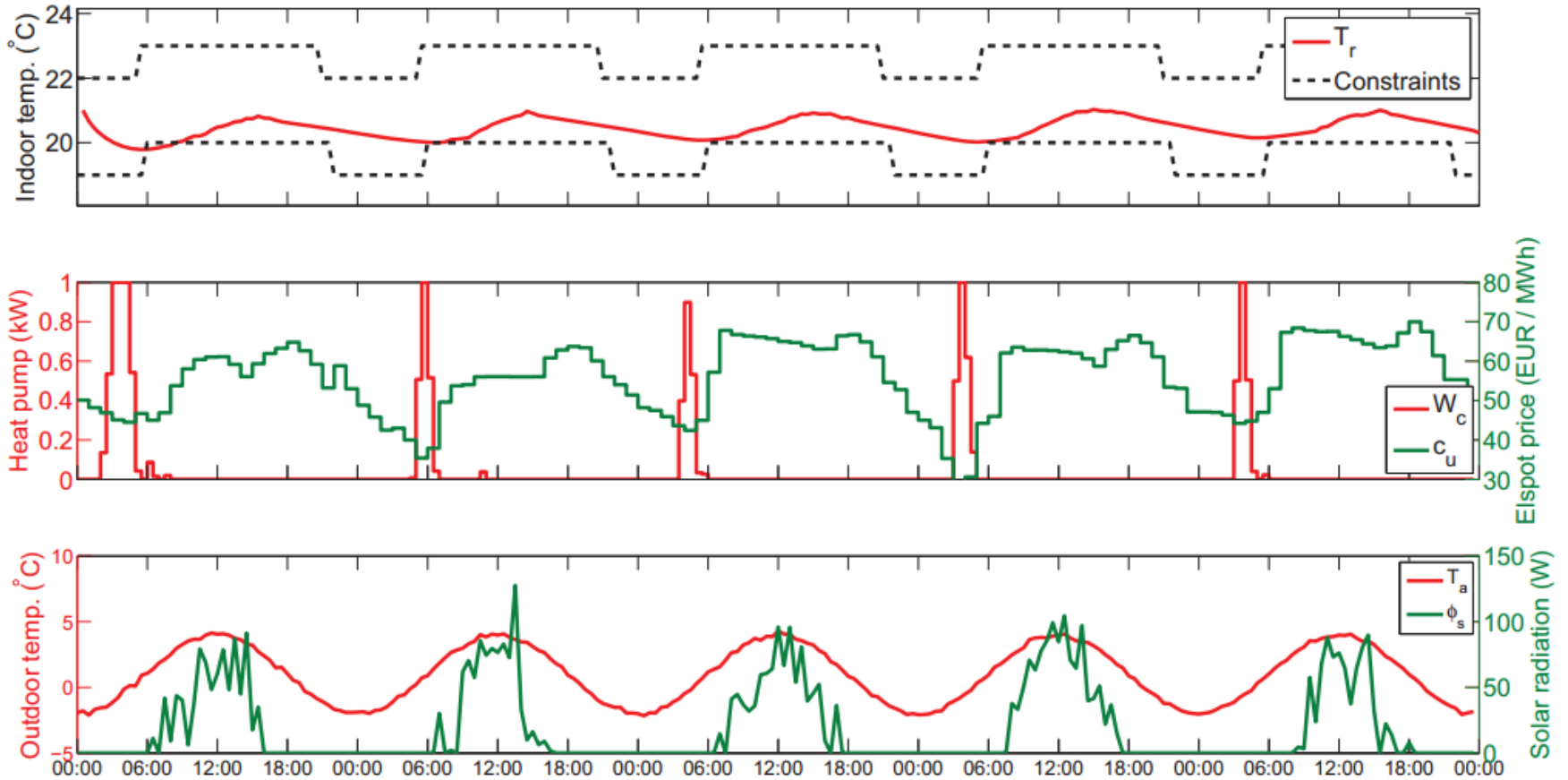
Scientific advances in Economic MPC to enable smart energy homes



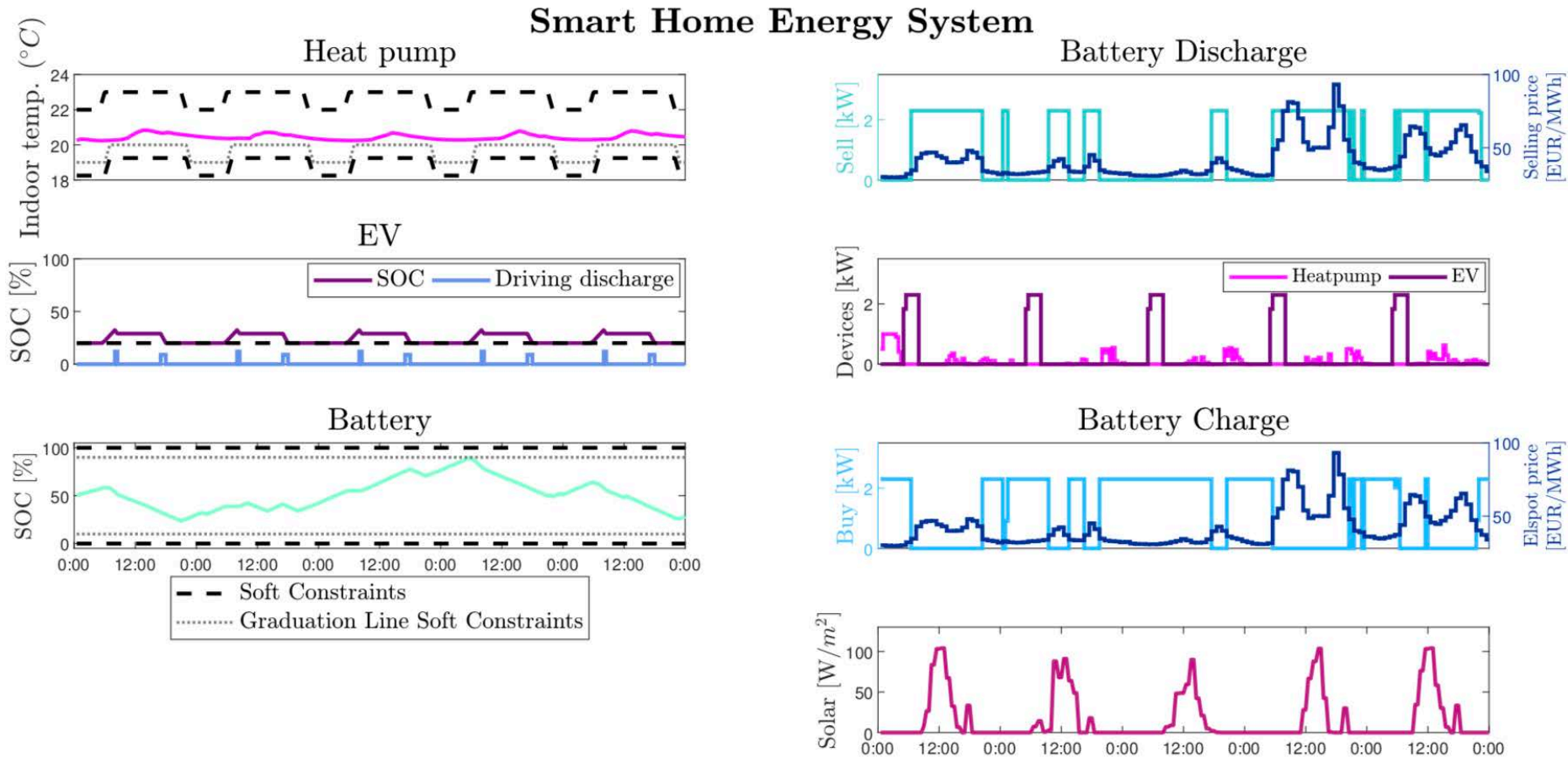
Economic MPC for Smart Energy Homes – a number of scientific advances

- Multi-level soft constraints
- Cost-to-go function – value of energy stored at the end of the prediction horizon
- A simple model for simulation, control and optimization of such systems
- Efficient algorithms and computational technologies

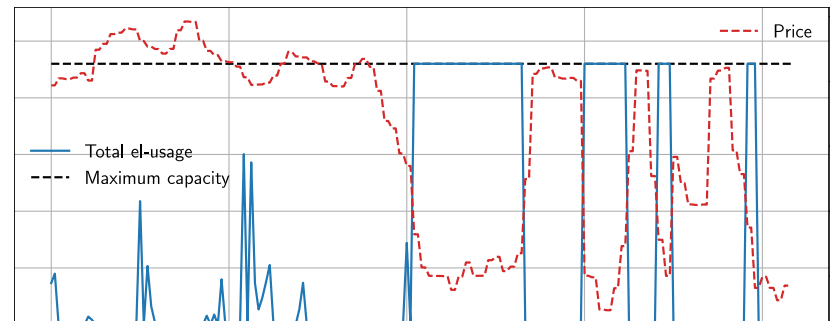
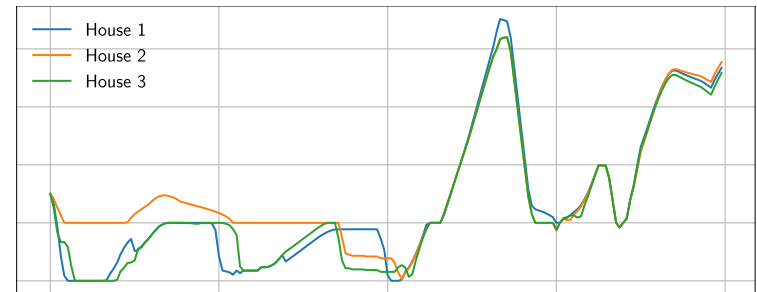
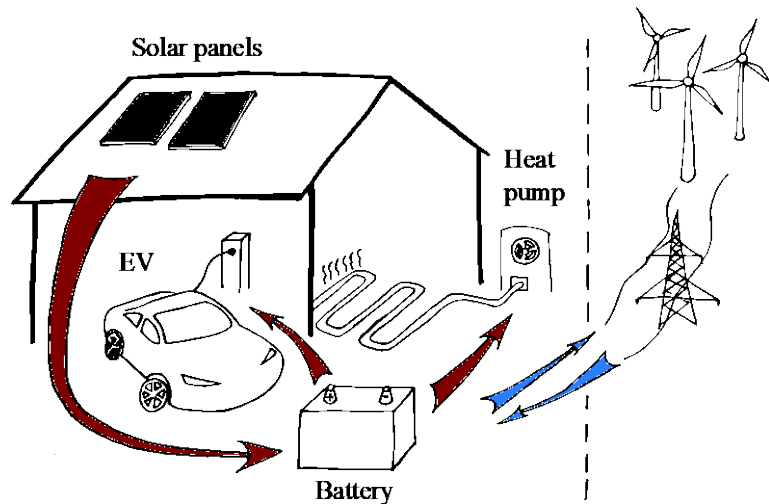
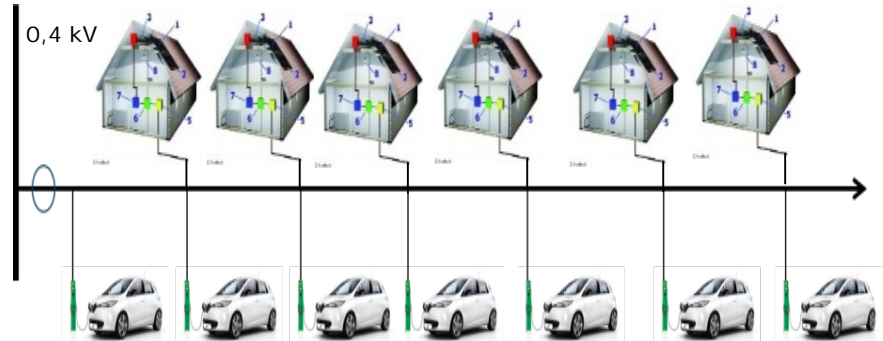
Economic MPC for Building Climate Control



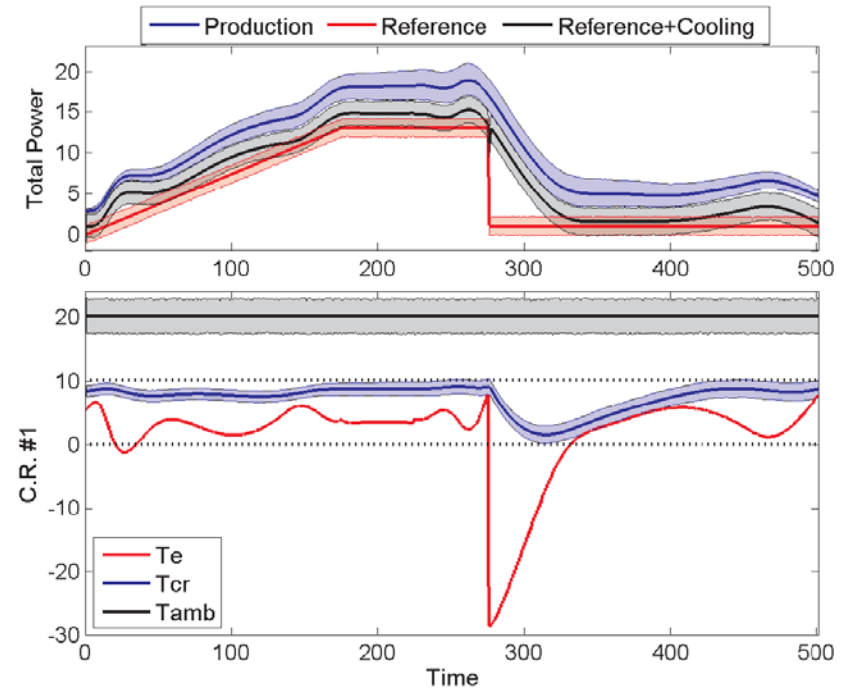
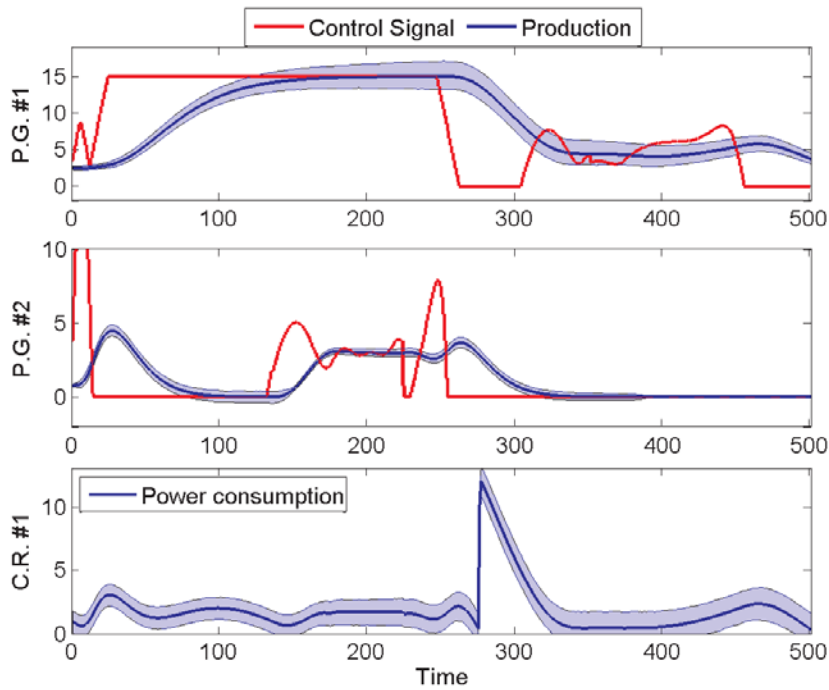
Model Predictive Control for a Smart Energy Home – Simulation Results



A neighborhood of smart energy homes - Lærkevej

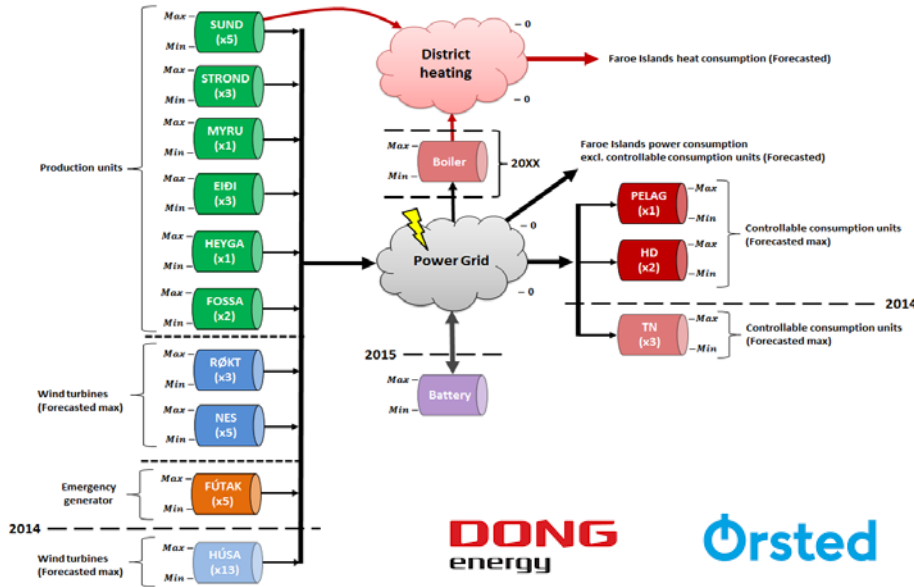


Supermarket Refrigeration – Demand Response

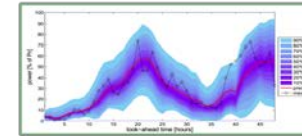




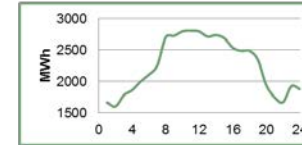
The Faroe Island Power System



Wind Power Forecast



Consumption Forecast



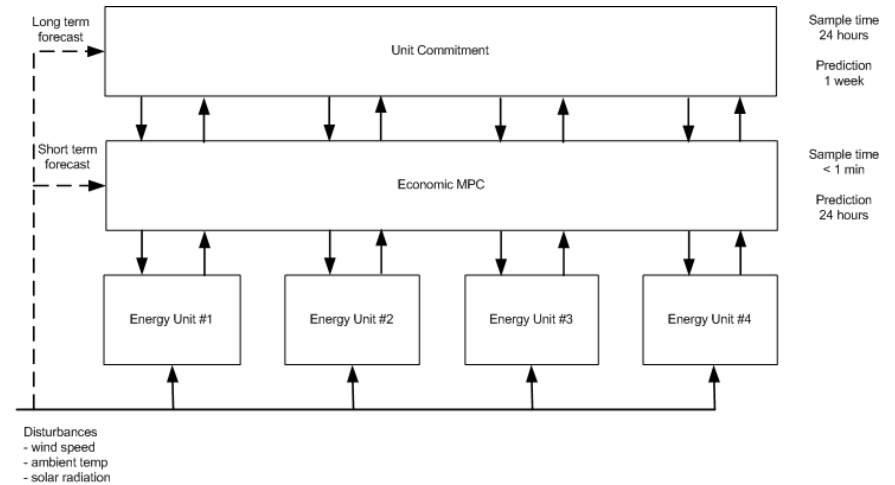
Unit Specifications



Plan



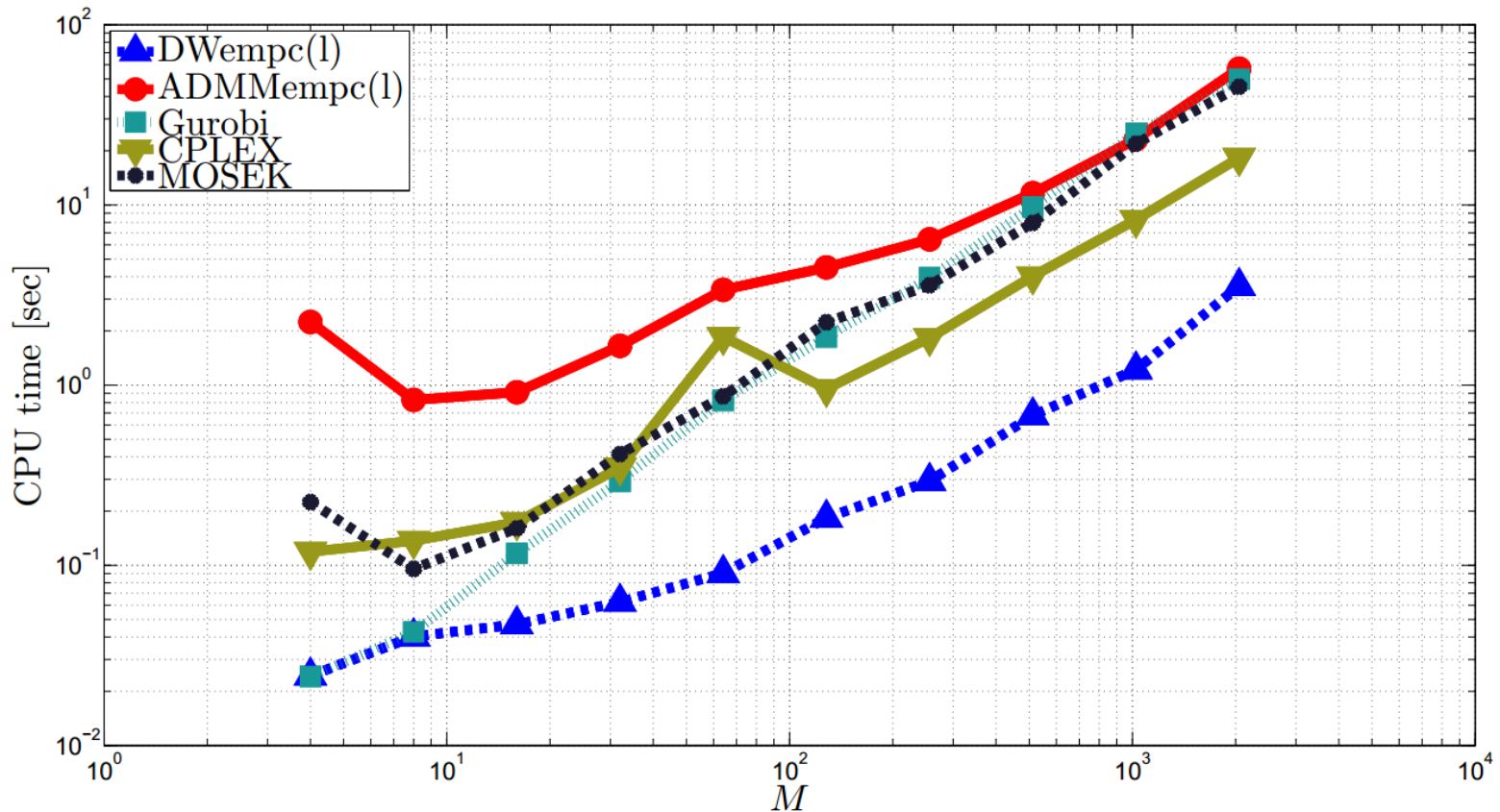
- Controlled the entire Faroe power system for 3 months
- Economic MPC system developed by Orsted (Dong Energy) and DTU Compute as part of an industrial PhD project



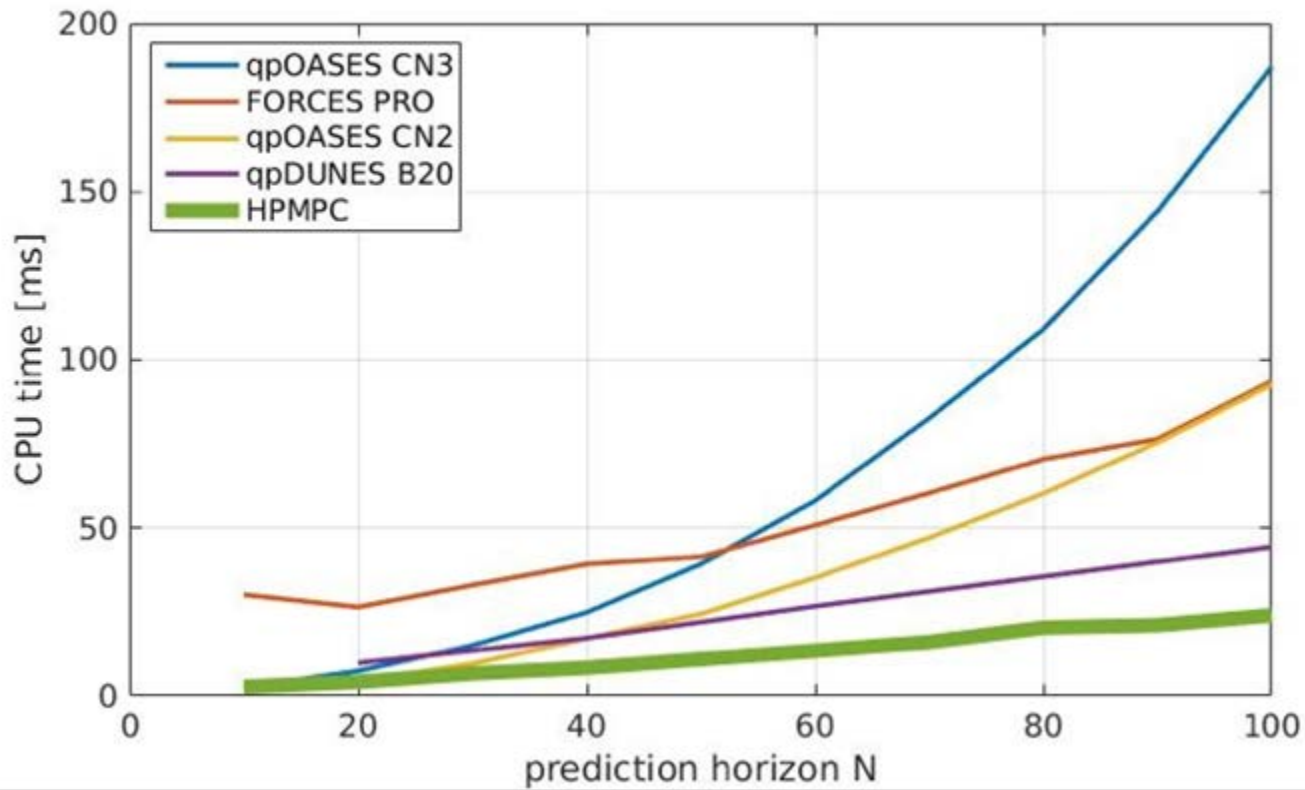
Fast Solver for Direct Control of an Entire City

A Dantzig-Wolfe Decomposition Algorithm for
Linear Economic Model Predictive Control of Dynamically Decoupled Subsystems

L.E. Sokoler^{a,b}, L. Standardi^a, K. Edlund^b, N.K. Poulsen^a, H. Madsen^a, J.B. Jørgensen^{a,a}

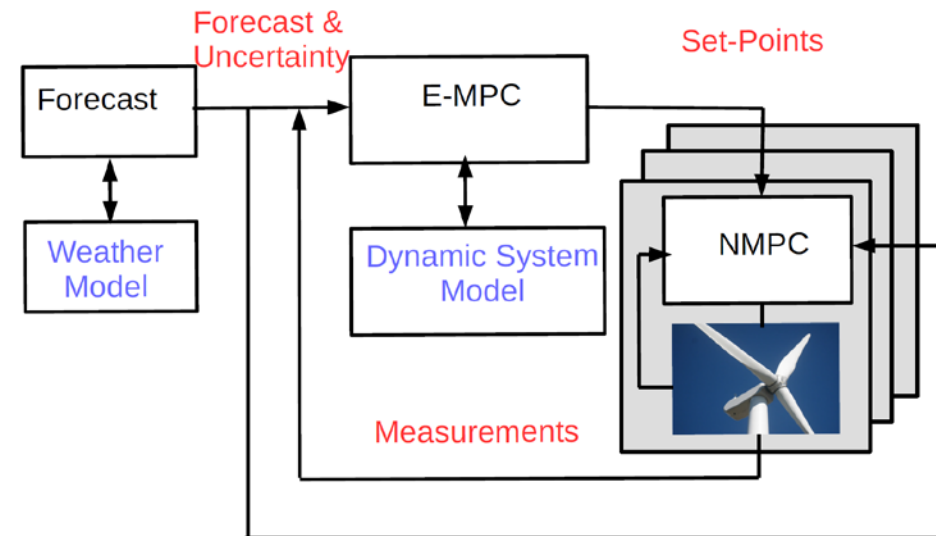
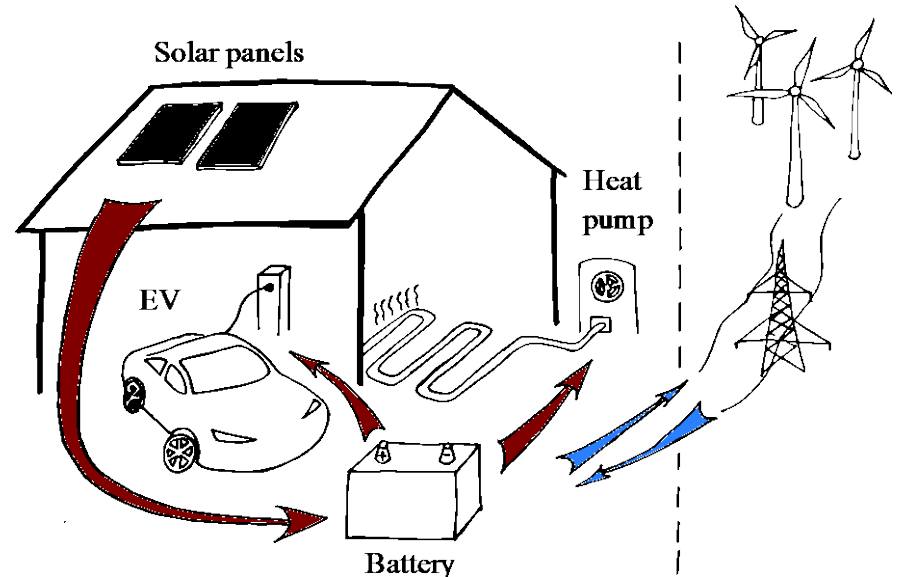


Fast Algorithms for Model Predictive Control - enable new applications



Summary

- MPC technology implemented in many systems to enable coordinated and efficient operation
- Industrial energy related processes
 - Cement Processes (FLSmidth)
 - Food processes (GEA Process Engineering)
- Energy Processes
 - Energy system control (Orsted)
 - Wind turbine control (Vestas)
- MPC technology is mature and ready to be implemented on large scale for buildings to enable smart cities and smart energy homes.
- MPC technology is the key enabler for integrated and coordinated systems





Thank You – Q&A



Smart Cities
Accelerator



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DTU Compute

Department of Applied Mathematics and Computer Science

